CANADIAN CLIMATE CENTRE

REPORT NO. 91-6

Enhanced Greenhouse Warming:

Regional Response and Believability

by

David Etkin

ATMOSPHERIC ENVIRONMENT SERVICE

DOWNSVIEW, ONTARIO

1991

THIS REPORT HAS RECEIVED ONLY LIMITED CIRCULATION BECAUSE OF THE SPECIAL NATURE OF THE PROJECT. HOWEVER, REFERENCE IS PERMITTED IF THE WORDS "UNPUBLISHED MANUSCRIPT" ARE MADE PART OF THE BIBLIOGRAPHIC ENTRY, IN ACCORDANCE WITH ACCEPTED PRACTICE.

OTHER CANADIAN CLIMATE CENTRE (CCC)
SCIENTIFIC SERIES INCLUDE:

1.	CS series	- CCC Climatological Study
2.	CLI series	- CCC Climatological Memoranda
3.	CDS/DS series	- CCC Climatic Data Summary
		- CCC Documentation Sheet

For further information on climatological publications contact the

Climatological Services Division
Atmospheric Environment Service
4905 Dufferin Street
Downsview, Ontario M3H 5T4

Enhanced Greenhouse Warming: Regional Response and Believability

by

David Etkin

A publication of the Canadian Climate Program

93-00191/

Table of Contents

Abstract 1

Introduction 2

Background 4

How well can climate models reproduce current climate 6

A paleo and historical perspective on arctic climate change 7

Climate prediction 11

Regional climate change 15

Climate change and the Mackenzie Valley 17

Regional climate impact studies 22

Conclusions and recommendations 25

References 27

1 Abstract

Climate models predict significant changes in the world's climate over the next 50 to 100 years due to increasing atmospheric greenhouse gases. To what extent these predictions can be believed has been the subject of considerable scientific debate. It seems reasonable to conclude that significant changes in climate, perhaps rivaling the last transition into an interglacial period, are likely. The confidence one can have in climate predictions decreases with scale, such that below a continental scale one cannot consider climate predictions from numerical models to be a reasonable guide to future trends.

Résumé

Les modèles climatiques prévoient les changements importants que le climat subira au cours des 50 à 100 prochaines années du fait de la hausse de la concentration des gaz à effet de serre dans l'atmosphère. Dans quelle mesure peut-on se fier à ces prévisions? Cette question a fait l'objet de maints débats scientifiques. Il semble raisonnable de conclure à la probabilité de changements climatiques importants, qui rivaliseront peut-être avec la dernière transition ayant conduit à une période interglaciaire. La confiance qu'on peut porter aux prévisions climatiques décroît avec l'échelle, si bien qu'au-dessous d'une échelle continentale les prévisions climatiques des modèles numériques ne sauraient donner d'idée valable des tendances à venir.

2 Introduction

The purpose of this paper is to consider to what degree one can have confidence in climate predictions, specifically around the issue of greenhouse warming due to increasing radiatively active gases such as carbon dioxide. Since the issue of scale is very significant to users of climate predictions in regional impact studies, the relationship between scale and confidence is considered in some detail, using one region (the Mackenzie Valley) as an example.

In order to discuss believability, it is first necessary to consider the issue of greenhouse warming per se, before focusing on regional response. Other issues fundamental to believability are how well current climate can be specified through the use of data sets, how well climate models can specify current climate and how predicted climate change fits into what is known about how climate has changed in the past. A range of opinions is shown in order to provide the reader with an appreciation of the divergence of views that exist with respect to this topic, while at the same time emphasizing prevailing scientific opinion.

There have been so many scientific papers written on the subject of greenhouse warming, and so many articles in the public press, that the imminent threat of climate change to man and the ecosystem has become part of the scientific, public and political paradigm. For example, former UN Ambassador Stephen Lewis refers to us as being

> "on the edge of the cliff looking into the precipice", Lewis (1988).

while the statement from the Toronto conference 'The Changing Atmosphere: Implications for Global Security', June, 1988 states that:

> "Humanity is conducting an unintended, uncontrolled, globally pervasive experiment whose ultimate consequences could be second only to a global nuclear war...The best predictions available indicate potentially severe economic and social dislocation for present and future generations, which will worsen international tensions and increase risk of conflicts between and within nations. It is imperative to act now."

Certainly the public press often presents scientific results in, to say the least, a colorful manner; nevertheless the scientific community in general is expressing grave concern over the likely implications regarding climate change. M.C. MacCracken, editor of two U.S. DOE state of the art reports dealing with CO_2 induced climate change (detection and prediction) is of the opinion that:

> "Carbon dioxide is essential to life on Earth, and changes in its concentration will set off a chain of responses involving many interacting processes. The climate will surely respond in important ways." (MacCracken, 1985).

Yet at the same time there have been pockets of skepticism, such as the Marshall Institute (Marshall, 1989), which states that:

> "Current forecasts of the man-made greenhouse effect do not appear to be sufficiently accurate to be used as a basis for sound national policy decisions. Policy makers would be wise to invest in the additional resources needed to improve the reliability of greenhouse forecasts before undertaking corrective programs that could turn out to be unnecessary..."

by S.B. Idso who concludes that:

> "A millenial perspective of Earth's temperature and CO_2 histories argues against (but, obviously does not yet totally disprove) the popular and widely held view that the conventional CO_2 greenhouse effect is as strong as it is generally portrayed to be" (Idso, 1988) and finds it "hard to believe that the current CO_2/trace gas greenhouse effect theory is not grossly in error" (Idso, 1987).

and by Richard S. Lindzen:

> "The current state of our understanding of climate hardly justifies a consensus over the response of climate to the small increase in downward flux caused by a doubling of CO_2" but also notes that "...the possibility of a significant greenhouse warming remains..." (Lindzen, 1990).

The scientific basis of portions of the Marshall report have come under serious question, especially relating to their analysis of sunspots and solar constant and their effect upon the earth's surface temperature, and the incorporation of ocean in terms of the transient climate response (Gordon McBean, personal communication, 1990; Dr. McBean is a professor of Geography at the University of British Columbia). Similarly the scientific basis for some of the arguments presented by S. Idso have come under serious criticism as he uses equations applicable only to equilibrium conditions with a set of non-equilibrium data in order to estimate climate sensitivity under equilibrium (Luther and Cess, 1985). Certainly however, uncertainties are large and critics play an essential role in forcing the mainstream scientific community to maintain perspective and validate the assumptions upon which their work is based.

A more dispassionate quote which seems to sum up our dilemma eloquently can be taken from Stephen Schneider:

> "...slowing down our pollution of the atmosphere is international insurance against the uncomfortable risks of future nasty surprises. Despite the uncertainty over details, to delay action is to commit the Earth and its inhabitants to larger amounts of more rapidly occurring environmental change than if we act now. The dilemma rests, metaphorically, in our gazing into a very dirty crystal ball. The tough problem is how long we clean the glass before we act on what we think we see inside." (Schneider, 1988).

3 Background

The sun is the ultimate engine which drives the earth's climate. Radiation from the sun reaches our atmosphere and undergoes a complex process of reflection, absorption and re-emission within the atmosphere and at the surface of the earth. It is a necessary physical condition that, over the long term, a radiative equilibrium be achieved between the amount of radiation incident upon the earth and the amount reflected and re-emitted, but there are many ways in which this equilibrium can be reached depending upon the physical configuration of the earth-atmosphere system. If the earth were totally ice covered, much more of the high energy short wave radiation from the sun would be reflected back to space; the earth would be very cold but still in radiative equilibrium. If the earth were a black body (but still enveloped by our atmosphere with its greenhouse gases) then it would absorb all the short wave energy reaching it and emit it out to space at much longer wavelengths. In this scenario the earth would be hot but again, still in radiative equilibrium.

The reality of the radiative dynamics lies between the two scenarios described above, and is complicated by a net radiative deficit at the poles and a net radiative surplus at tropical latitudes, which creates the physical necessity for longitudinal heat transport in order to balance the system. The amount of radiation absorbed and then emitted back out to space at longer wavelengths, and the amount reflected depend upon a number of factors including the amount of snow and ice on the earth's surface; the concentration within the atmosphere of various gases which have the ability to absorb radiation at wavelengths emitted by the earth or sun (greenhouse gases); cloud amount and optical properties; and the albedo of the different reflecting surfaces. "Overall the surface energy balance is dominated by longwave radiation (the greenhouse effect)" (Gutowski et al., 1988).

Over time, many of these factors vary. For instance, the amount of radiation reaching the earth from the sun (the so-called solar constant) varies depending upon various orbital

parameters and sunspot cycles. Changes in the eccentricity of the earth's orbit with a period of 100,000 years account for about 0.2% variation in the solar constant (about 0.7 Watts/m^2). The amount and spatial distribution of landmass and ocean have important implications with respect to absorption of solar energy, and these change on very long time scales due to continental drift. The main reason for hemispheric climate asymmetry is that of different ocean-landmass distributions, especially at polar latitudes. These asymmetries may well result in climatic change behaving very differently in the two hemispheres. Researchers have noted that in a recent coupled ocean-atmosphere model run with a gradual increase in carbon dioxide, the model showed a "marked and unexpected inter-hemispheric asymmetry" (Stouffer et al., 1990). The radiative characteristics of the earth-atmosphere also vary, due to both natural and anthropogenic causes.

The much publicized issue of greenhouse warming deals with this last factor, ie. changes in the radiative characteristics of the atmosphere due to the practices of man's civilization, specifically increasing concentrations of radiatively active gases such as carbon dioxide, methane, CFC's, etc. It is estimated that a doubling of CO_2 will result in a net radiative heating of about 4 watts/m^2 (Ramanathan et al., 1987). What is special about what man is (potentially) doing to the climate is not only the change that may occur as a result, although that is important, but the <u>rate</u> at which it may change. By the end of the last ice age, about 10,000 years ago, much of Canada was covered with a thick ice sheet, and the global average temperature was about 5°C colder than present. The subsequent warming to an interglacial period may have occurred over a time frame as short as a few centuries (Sutherland, 1990). As a result of the rapidly changing concentration of greenhouse gases (Ramanathan et al., 1987), numerical models predict a rate of climatic change possibly exceeding any which has occurred during the presence of man on the planet (Schneider, 1989; Etkins, 1989), a warming perhaps several times more rapid than that which occurs between an ice age and an interglacial. The potential consequences of greenhouse warming and the implications in terms of adaptation are profound.

The issue of whether historical data support the greenhouse warming theory has been the subject of a considerable amount of attention. A study by Schlesinger (1986a) suggests that the atmospheric e-folding time (the time required for the climate to approach equilibrium by a factor of 1/e after a disturbance to the CO_2 levels in the atmosphere) is between 50 and 100 years as a result of the transport of the surface heating into the oceans. The precise value of the e-folding time is difficult to estimate, since it depends quadratically on the climate system gain and linearly on the thermal diffusivity of the ocean (Schlesinger, 1986a). It is thought that about half of the warming resulting from CO_2-induced surface heating has been sequestered into the oceans, and that the lag built into the

system will result in continued warming even if CO_2 levels were to remain unchanged. Climate trend analysis indicates that the earth has warmed about 0.5°C during the past century (Jones et al., 1986; Vinnikov et al., 1990), and this appears to be within the range of natural variability, although a few scientists (e.g. Hansen et al., 1989) are convinced that greenhouse warming is already evident. In the period 1980 to 1989, five of the warmest years on record occurred. The probability that this occurred within the bounds of natural variability is between 1% and 3.2% (Tsonis and Elsner, 1989; Hansen et al., 1989). However, an examination of the probability that climate trends during the past century were or were not due to internal climate processes, through an application of chaos theory was inconclusive (Lorenz, 1989). Sufficient evidence is simply not yet available in order for us to be certain of detection, although the weight of evidence may support the hypothesis that we are in the beginnings of a period of climate warming.

4 How well can climate models reproduce current climate

There are two parts to this question, firstly how well do our data sets specify the earth's climate, and secondly how well do climate models reproduce that specification. Differences between the models and data sets could be related to errors in either, or more fundamental differences in exactly what is being measured or modelled.

Climate is usually specified using 30 years of data, in order to determine averages, variances, return periods etc. Exactly what is meant by current climate, in the presence of a climate trend is somewhat ambiguous, since statistics generated from one 30 year period (such as 1951 to 1980) are not likely representative of the beginning or end point of the time frame, or indeed (especially!) a future period; however, for the purposes of definition, current climate will be defined as a set of statistics generated using 30 years of recent data.

In order to define climate, data are needed. Data have been historically gathered through the use of meteorological instruments, distributed across a land- and ship based network. Over time, observing locations, observing methods and instrumentation change. While in some regions there are many observing sites, this is not generally true, especially over the oceans and lakes and polar regions. The problem of specifying current climate, given an inadequate global density of often non-stationary observing stations (which in some areas such as the Arctic are also of debatable representativeness) is non-trivial, to say the least. Modern satellite-based remote sensing tools are beginning to make substantial improvements in this area and in the future we will be able to specify climate much more accurately.

Comparisons of climate models run in a control mode (ie. $1xCO_2$) with observed global temperature distributions (Grotch, 1988) reveal significant errors of the same magnitude as the warming predicted in $2xCO_2$ climate predictions.

5 A paleo and historical perspective on arctic climate change

The climate of the Holocene period (back to about 10,000 years before present) and of a recent geologic time frame (back to about 100,000 years before present) has been summarized in AES (1985). These data are inferred from such sources as ice cores, tree rings, fossil pollen, etc., and cannot be considered to be as accurate as directly measured data. On a historical time frame, Figures 1, 2 and 3 show trends from proxy (AES, 1985) and instrumental records (Wigley et al., 1985), on several geographical scales. Note that Figure 2 indicates that the Mackenzie began a cooling period around 4000 BP, somewhat later than other arctic regions. More recently the Arctic showed a warming trend from the late eighteen hundreds until 1940, a cooling trend from 1940 to 1960, and a warming trend after 1960. These trends have been recently confirmed by Vinnikov et al. (1990) using an updated USSR data set corrected for inhomogeneities. Arctic temperatures tend to be more variable than hemispheric, and although this is generally true as one goes to smaller scales due to the averaging process involved, it is much more true for the Arctic. This tends to result from two factors. Firstly, arctic climate is particularly sensitive to changes in global energy balance or circulations or small perturbations in the strength and patterns of currents in the North Atlantic and Pacific Oceans (Roots, 1989). As well, the arctic airmass, particularly in winter, is different from all other airmasses in that it is baroclinic in nature (ie. strong temperature gradients exist within the airmass). This high variability makes it difficult to detect trends, since it creates signal to noise ratio problems.

130 000 BP

GENERALLY WARM AND WET

120 000 BP

PRECIPITATION GREATER AND TEMPERATURE ABOUT THE SAME AS AT PRESENT

70 000 BP

COLDER AND DRIER

15 000 BP

WARM AND WET

10 000 BP

Figure 1. Canadian Arctic climate trends on a geologic time scale (AES, 1985).

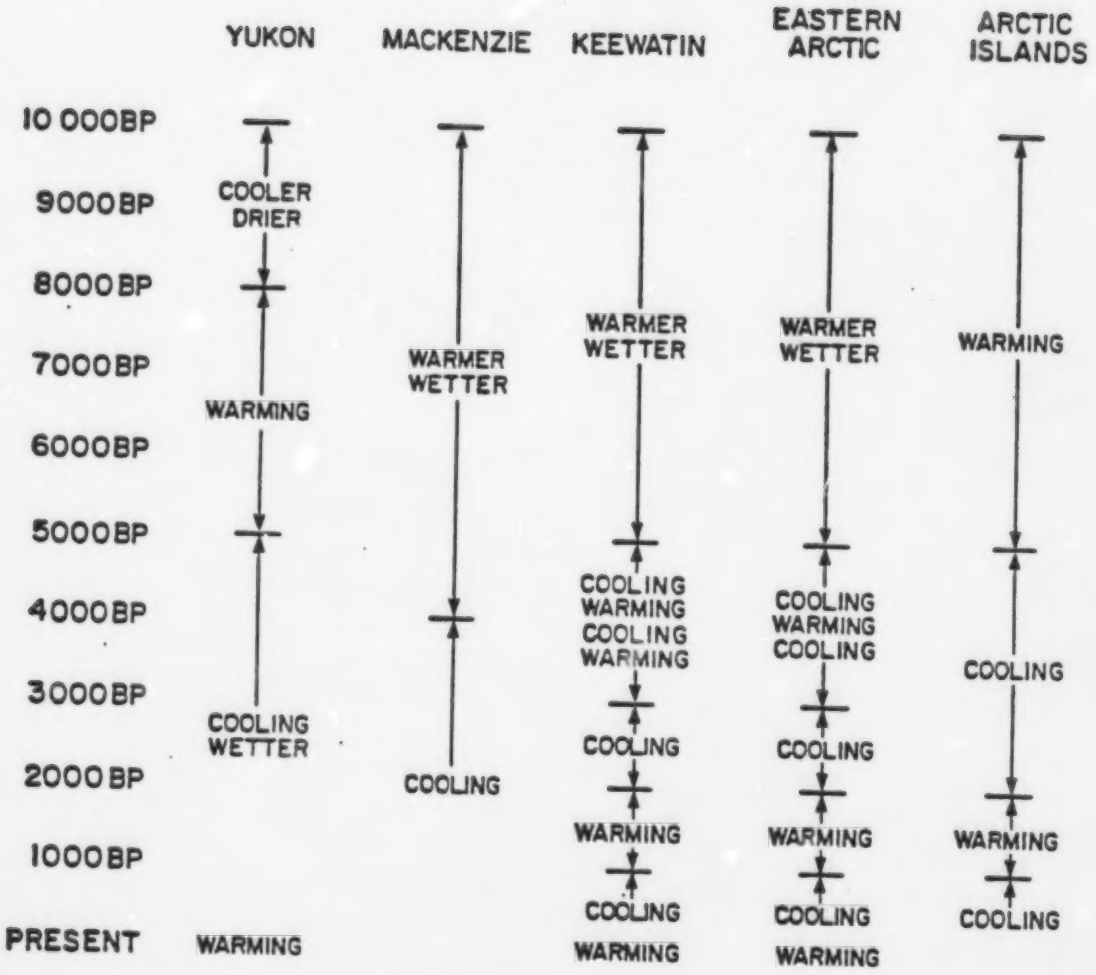

Figure 2. Canadian Arctic climate trends in the Holocene (AES, 1985).

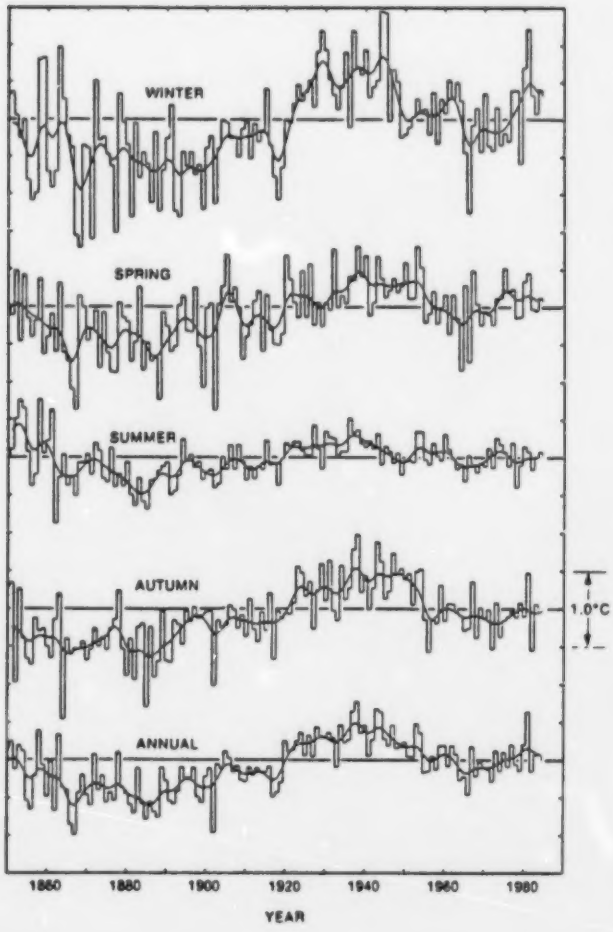

Figure 3. Arctic (65-90°N) surface air temperature fluctuation by season (Jones et al., 1988).

6 Climate prediction

Predicting future climate is very difficult, therefore most impact studies use the output from several models, which may be quite different in various ways. Due to the low level of confidence in any specific model output, the various climate predictions are called scenarios, and are used to depict a range of possible outcomes. Generally a scenario is a self consistent climate depiction based upon a historical, paleo or numerical model.

The study of historical and paleo climates provides information on how the climate system operates, and may be useful to provide analogues of future climates. There are problems however, related to different boundary conditions in the past as compared to the present and future (Crowley, 1990); transient climate response during a period of rapid change; and the ability of reconstruction methods to accurately specify past climates.

The best tools for understanding and predicting future climate changes are likely numerical models. The simplest type of model, a zero-dimensional model, with CO_2 concentrations increased from 300 to 600 ppm results in a surface temperature increase of about 1.2°C (Cubasch and Cess, 1990). However, the real system is much more complicated, and subject to many feedback loops, both positive and negative, not included in zero-dimensional models. Overall, these feedback loops, which are not completely understood, appear to act so as to amplify the enhanced greenhouse surface temperature change (Lashof, 1989). The most important loops involve the ocean (changes in circulation patterns and deep water production which could significantly alter the pattern of regional climates are possible [Watts and Morantine, 1990]); water vapour (doubling of CO_2 should increase atmospheric water vapour, an important greenhouse gas, by perhaps 20-33% [Folland et al., 1990]); ice and snow cover (as important factors in positive feedback loops with respect to radiation); and cloud (clouds can produce a positive or negative feedback, depending upon the model). Models can be quite sensitive to the particular parameterization used to describe these loops (Mitchell, 1989; Meehl and Washington, 1990).

In order to understand the way in which the climate system operates, more complicated three-dimensional climate models have been developed (general circulation models or GCMs). A summary of the physics of three such models is described in Schlesinger and Mitchell (1985). Uncertainties in the models are large and not quantifiable (Schlesinger, 1984), and these uncertainties are the basis of most of the criticism relating to decision making based on their outputs. A recent EPA state of the art report noted that:

> "Uncertainties about climate feedbacks from clouds, vegetation, and other factors make it difficult to predict the exact amount of warming that a given level of greenhouse gases, such as doubled carbon dioxide concentration would cause. How quickly climate may change also is not known, because scientists are uncertain both about how rapidly heat will be taken up by the oceans and about some climate feedback processes." (Smith and Tirpak, 1989).

General circulation models run in a $2xCO_2$ mode show global warming to be $3.5^{o}C \pm 1.5^{o}C$ (Bolin et al., 1986). An assumption inherent in these predictions is that no changes occur in the physical processes which force the climate system other than greenhouse gas concentrations. These figures represent model outputs for a climate in equilibrium (and usually in which the CO_2 has been doubled instantaneously), a situation which does not occur naturally since CO_2 is increasing in a continuous fashion and various lag responses are built into the climate system; as such the model outputs are somewhat removed from reality. As well, they should not be considered as an end point since a $2xCO_2$ world will only exist for a brief period of time, after which a $(2+epsilon)xCO_2$ world will exist, for another brief period. Washington and Meehl (1989) in their discussion of a transient atmosphere-ocean coupled model make the important point that climate predictions from models based upon an instantaneous doubling of CO_2 (as most of the experiments have been so far) may not be good analogues of the climatic response to a slowly increasing CO_2 level. In fact, it is possible for coupled models to produce more than one equilibrium (Manabe and Stouffer, 1988), although it is uncertain whether or not the real atmosphere can respond in such a way. GCMs have been run in a transient mode (Washington and Meehl, 1989; Manabe et al., 1990), but drift in model output has resulted in a low confidence level in the scenarios generated (Roger Daley, personal communication, 1989; Dr. Daley is chief scientist at the Canadian Climate Centre). Washington and Meehl (1989) note that errors in their model produce tropical sea surface temperatures which are too cold and high-latitude temperatures that are too warm. As a result equilibrium rather than transient model results tend to be favored for climate change and impact assessments (for example, the work of the Intergovernmental Panel on Climate Change (IPCC)). Within the foreseeable future the climate will not be able to adjust to any specific atmospheric concentration of greenhouse gases since that concentration is highly time-dependent. Of significance is the path of climate change, a road towards shifts in means and patterns, as opposed to any estimate of a specific pattern which may or may not exist at some time in the future.

The scenarios discussed here refer mainly to average conditions. At least as important in terms of impacts is the issue of climate variability, how extremes and the return periods of extreme events might change (eg. ENSO events). A reduced

temperature variability and diurnal cycle during summer is likely, while modelled precipitation variability changes with the same sign as the precipitation change (Rind et al., 1989), generally increasing as the climate warms (note that Rind et al., 1989 also provided the caveat that "...model deficiencies can be expected to contaminate climate change estimates, both for mean changes and changes in variability"). At the same time hurricane intensity (their destructive potential could increase by 40-50%) and well as tropospheric instability are expected to increase (Hansen et al., 1989), which would contribute to a more extreme hydrological cycle. A theoretical analysis of the probable occurrence of temperature extremes (Wigley, 1988) concluded that with anticipated $2xCO_2$ related warming, events which occurred with a 300 year return period would be transformed into a 40 year return period.

Critics make a good point about our ability (or inability) to predict future climate, and their arguments are sometimes used as a basis for inaction in terms of policy making. On the other side of the coin, however, one must remember that uncertainty can cut both ways. If climate change might be much less than modelled by current GCMs, then it might also be much more. The fundamental physical theory of the greenhouse effect on atmospheric temperature is well developed and irrefutable; greenhouse gases in a 'normal' atmosphere are responsible for the earth's surface temperature being about 33°C warmer than it would otherwise be, and studies using paleoclimate data suggest a sensitivity of 3°C for a doubling of CO_2 (Budyko and Israel, 1987), a value very close to that obtained from numerical climate models. The argument in favor of an enhanced greenhouse effect becomes even more convincing when other evidence such as Antarctic ice cores is considered. These ice cores support the close relationship between CO_2 and temperature (Barnola et al., 1987), and although the cause and effect relationship is not clear it appears as if CO_2 changes may have played an important role in amplifying orbital forcing (Genthon et al., 1987).

It is important to understand the climate scenarios generated by GCMs within the context of the state of the art of numerical modelling. To quote Dr. Stephen Schneider:

> "...these models do a credible job of predicting the very large difference in temperature between winter and summer, Mars and Venus, some aspects of the ancient Earth, so that it is a good bet that the global scale temperature predictions are accurate to about 50%." (Schneider, 1988)

The significant question is... what information is believable from the GCM's and what information is not? Figure 4 (modified from Hengeveld, 1990) shows one picture of where the current scientific state of understanding lies. George Boer, chief of climate modelling at the Canadian Climate Centre presents an alternate view in table 1. So what are the

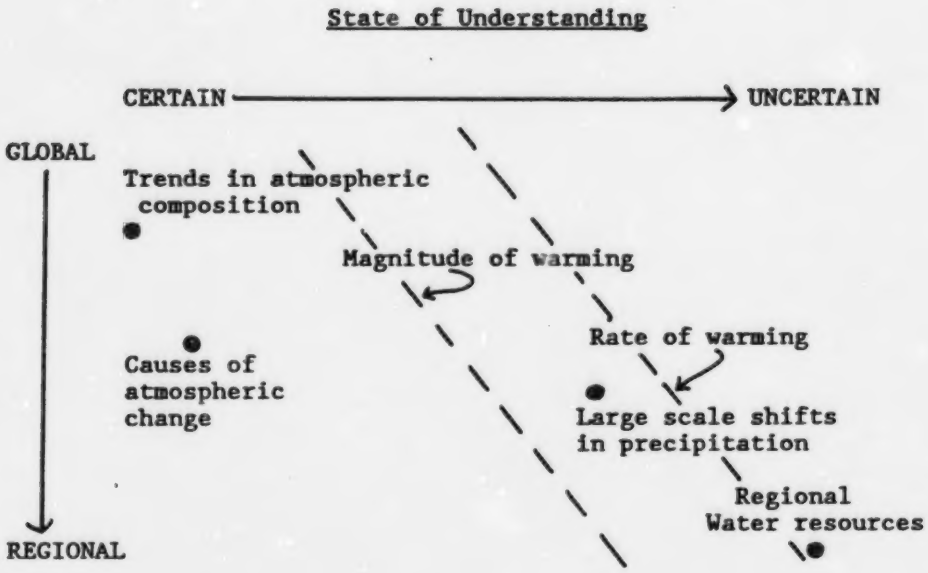

Figure 4. Uncertainty of climate prediction as a function of scale (modified after Hengeveld, 1990)

GCMs basically saying to us? As atmospheric radiatively active gas (RAG) concentrations increase so will global surface

Table 1
WHAT CAN WE BELIEVE?

	Current Level of Confidence		
	High	Medium	Low
Surface Warming			
Global Amount	X		
Latitude Amplification		X	
Local	X		
		<--------	X
Precipitation			
Global Increase	X		
Amount			X
Local			X
Soil Moisture			
Summer Dryness		<--------	X
Ice and Snow			
Decrease	X		

(George Boer, personal communication, 1990)

temperatures, and by a significant amount. Stratospheric temperatures are expected to decrease. Global precipitation will increase but a shift in patterns is likely. (It is interesting to note that Vinnikov et al. (1990) in an analysis of their global temperature and precipitation data set, found an empirical global mean annual precipitation sensitivity, on the continents between 35°N and 70°N, of +12%/°C which is several times higher than GCM model estimates.) Precipitation will also tend to become more convective in nature (Hansen et al., 1989) due to differential atmospheric warming in the vertical creating a more unstable atmosphere.

7 Regional climate change

There are a number of factors which cause increased skepticism regarding model outputs as one considers smaller scales. Whereas the ability of the GCMs to replicate current climate globally is fairly good, some regions do not do very well when compared to a $1xCO_2$ control run. A comprehensive regional comparison of climate simulations with four GCMs resulted in the conclusion:

> "although the models often agree well when comparing seasonal or annual averages over large areas, substantial disagreements become apparent as the spatial extent is reduced, particularly when detailed regional distributions are examined.... At scales below continental, the correlations observed between different model prediction are often very poor... the poor agreement between model simulations of the current climate on the regional scale calls into question the ability of these models to project the amplitude of future climatic change on anything approaching the scale of only a few (<10) gridpoints, which is essential if useful resource assessment studies are to be conducted" (Grotch, 1988),

and the EPA report previously referred to also noted that

> "Given the state of knowledge, it is difficult to assign probabilities to regional climate change... the scenarios provide a range of possible changes in climate for use in identifying the relative sensitivities of systems..." (Smith and Tirpak, 1989).

Hansen summarizes current thoughts on regional climate prediction as follows:

> "The conventional wisdom is that it is not yet possible to obtain reliable conclusions about regional climate impacts, principally for two reasons. First, the representations of atmospheric and surface processes in current climate models are highly simplified, and the models show a very wide range in their predictions for climate change at any particular region. Second, none of the existing climate models simulates the ocean realistically, and changes in ocean currents could alter regional climates... However, an increasing greenhouse effect undoubtedly implies some broad changes in the nature of regional climate, which it may be possible to investigate with existing modeling capabilities." (Hansen et al., 1989).

and this view is also supported in Bolin et al. (1986), who state that:

> "...present models are not yet able to simulate reliably the many processes that govern regional climate. However, comparison of model computations with observed features...has given us some confidence in available results" and go on to say that "The uncertainty is considerable, but there is almost unanimous agreement that a substantial warming would occur", with the caveat that "It does not seem likely that even intensified research will make it possible to

foresee the geographical patterns of a climatic change in more detail, before clear signs of an ongoing change are available".

Various climate feedbacks specific to the Arctic, involving the oceans, snow, ice and arctic haze (Harvey, 1988; Maxwell and Barrie, 1989; Etkin, 1990) create a unique environment with special modelling problems. A general description of climate change in polar regions is given in Roots (1989) and Etkin (1990). Arctic haze, a factor not included in GCM models can have an effect of 2°C or more (Harte and Williams, 1988; Blanchet, 1989). In the Arctic, temperature changes will be larger than those in more southern latitudes, especially in the late autumn and winter. The strength of the arctic inversion is expected to decrease. Surface flux differences between models of up to 100 W/m^2 occur near the edges of polar ice caps, as a result of different ice models in the GCMs and differences in control climate sea ice limits (Gutowski et al., 1988). In some models, summer sea ice in the Arctic and Antarctic disappear completely, while in others some remains, although very reduced in extent and thickness (Mitchell et al., 1990). Mitchell et al. (1990) also note that:

"On the basis of current simulations, it is not possible to make reliable quantitative estimates of the changes in the sea-ice extent and depth."

8 Climate change and the Mackenzie Valley

The climate of the Mackenzie Valley results from an interesting mix of climate controls, including topography, latitude, the Arctic Ocean to the north, and the proximity of the Aleutian low. Figures 5 and 6 illustrate the July and January temperature patterns of the Mackenzie Valley (Burns, 1974). The presence of the Mackenzie River Valley has a noticeable effect upon surface temperatures in the district. In the winter cold air drainage and the arctic inversion result in a cold pool of air lying in the Valley. As well this region is unprotected from outbreaks of arctic airmasses from the north, unlike Yukon. Winter temperatures in the Valley have been recently subjected to trend analysis, and have seen significant warming since the Burns analysis (Stuart et al., 1990); on the other hand, no significant precipitation pattern changes are discernible. This warming, which extends over Alaska as well (Figure 7), is greater than that experienced by any other area in the northern hemisphere over the last two decades (Jones et al., 1988), and appears to be related to the intensity of the Aleutian low (P.D. Jones, personal communication, 1990). During the summer the Valley experiences warmer temperatures than the surrounding area, due to the breakdown of the arctic inversion.

The climate of the Mackenzie region over the past 100,000 years is summarized in Figure 8 (AES, 1985). Delorme and Zoltai (1984) examined fossils from a peat deposit in the Mackenzie Delta, and determined that between 7200 and 8600 years before

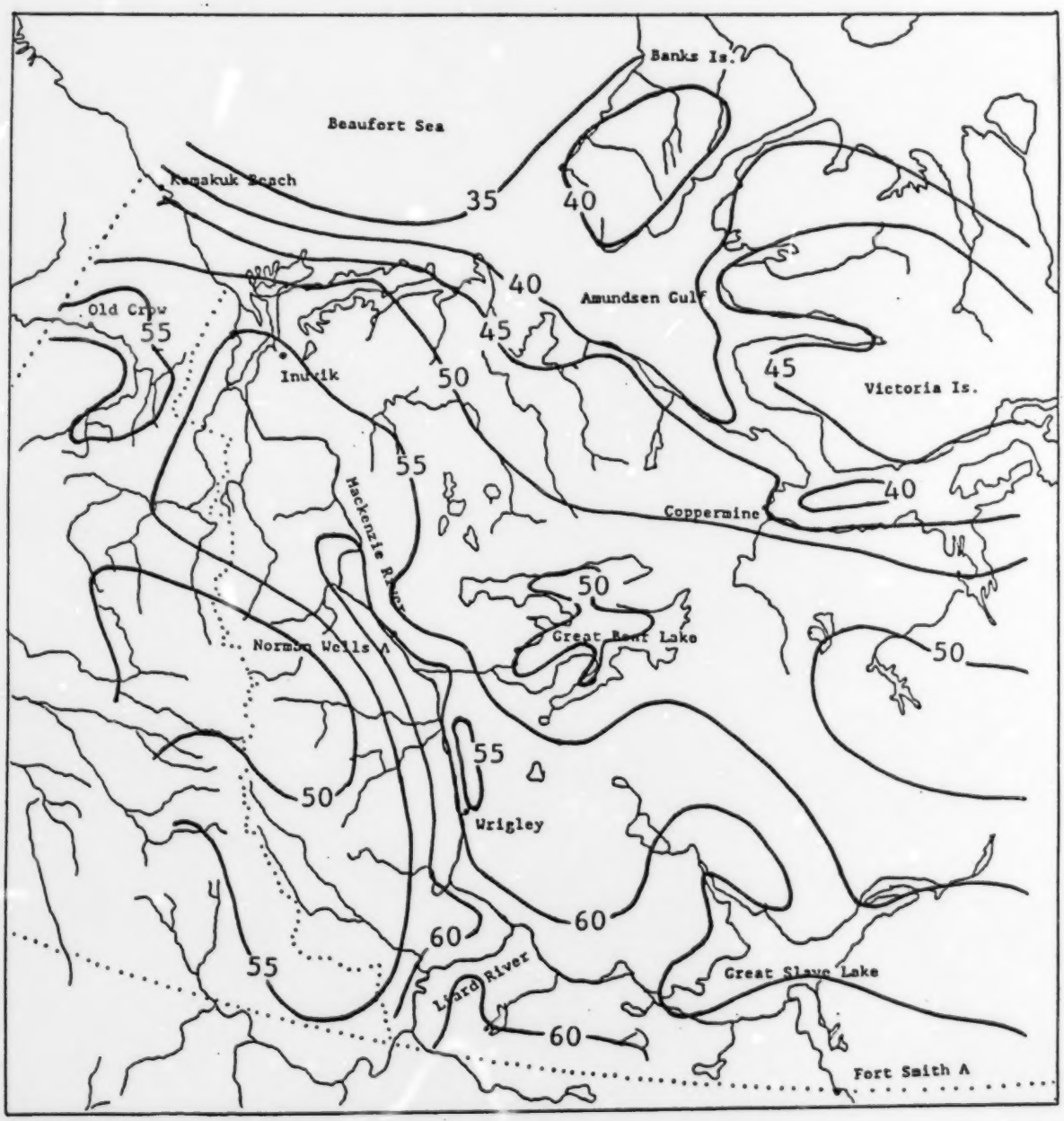

Figure 5. July mean daily temperature (^{o}F), based on period 1941 to 1970 (Burns, 1974).

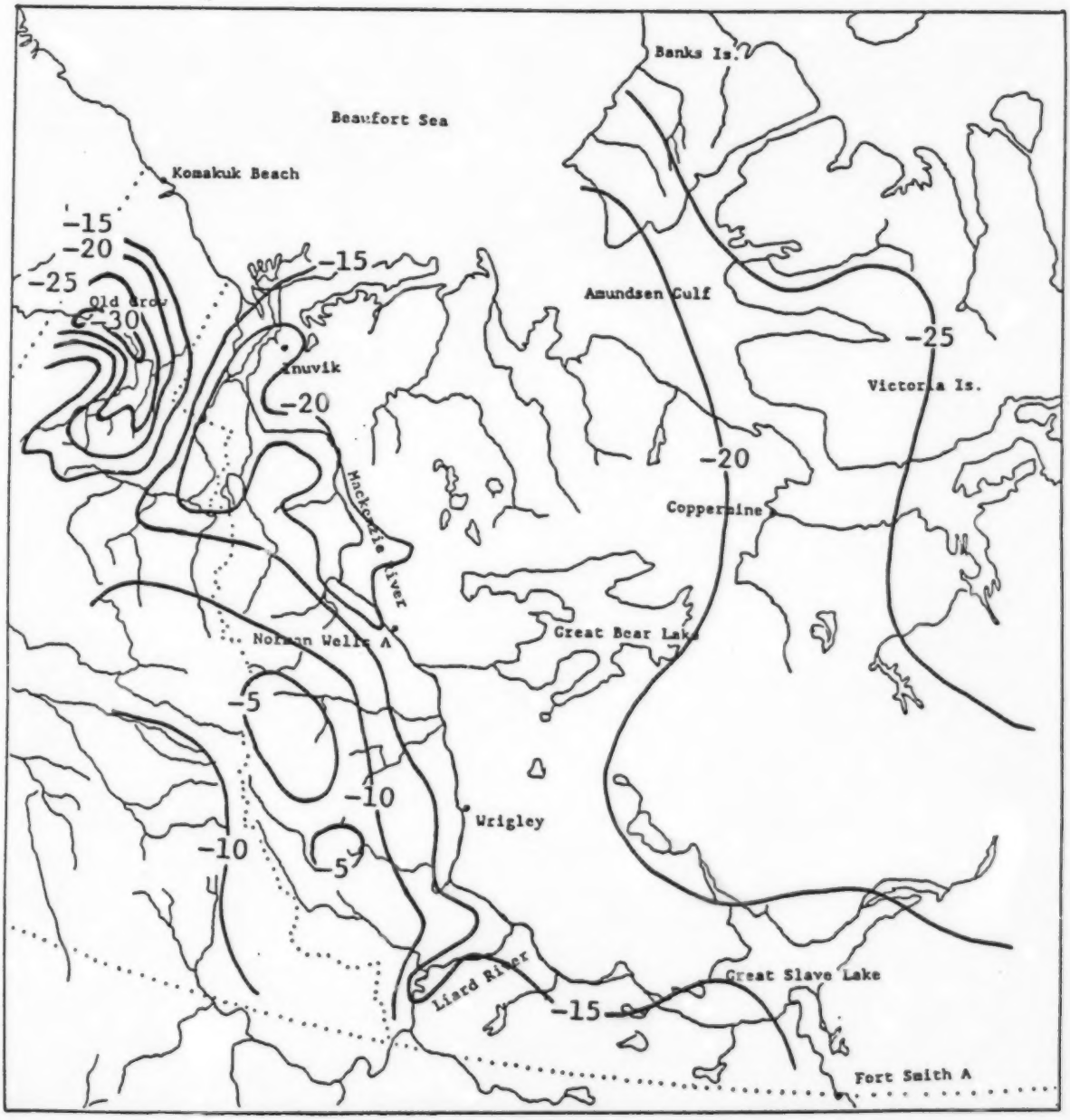

Figure 6. January mean daily temperature (^{o}F), based on period 1941 to 1970 (Burns, 1974).

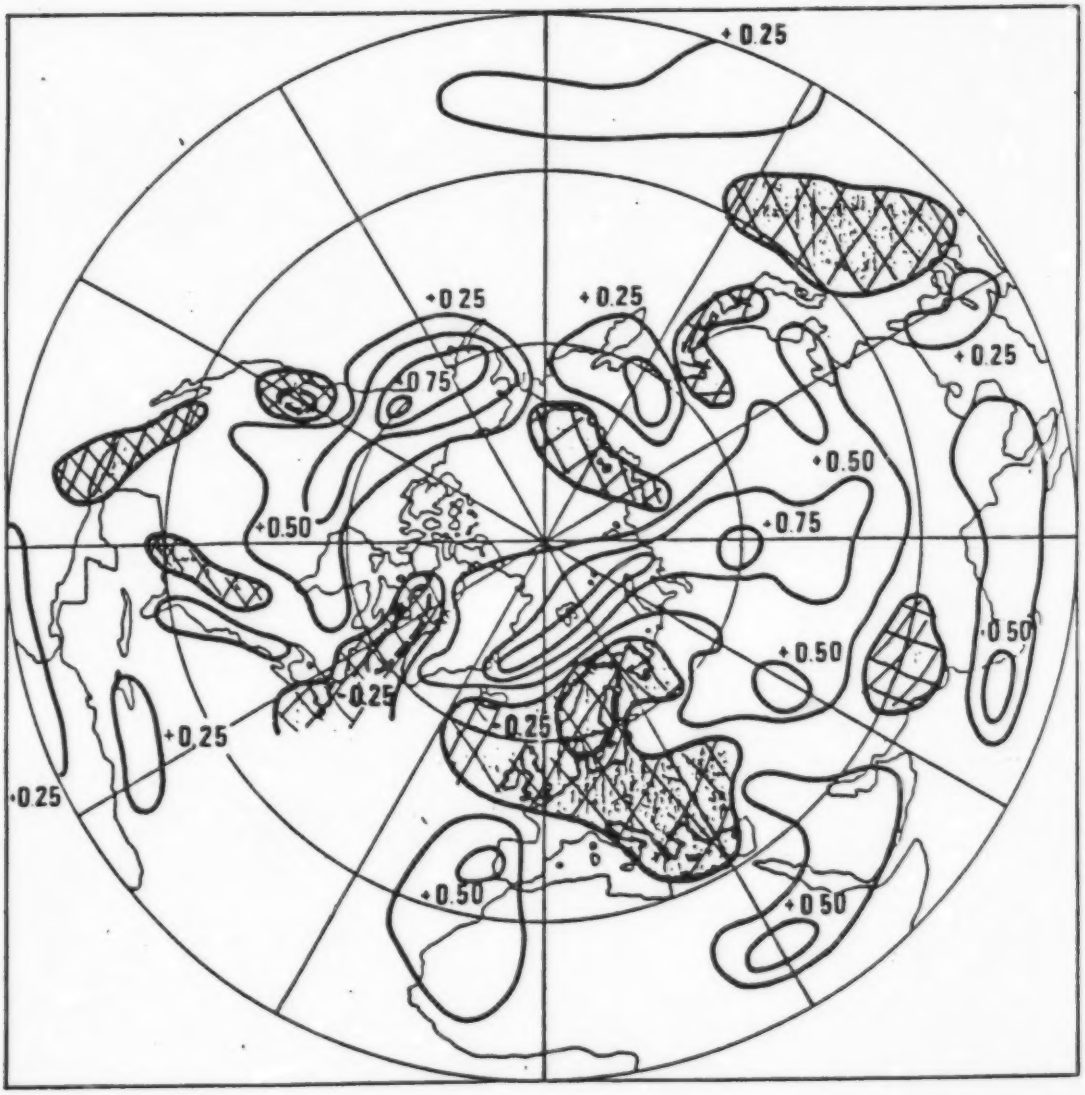

Figure 7. Linear temperature trends for the northern hemisphere in ^{o}C/decade (Jones et al., 1988). Hatched areas represent cooling and open areas represent warming. The largest warming in the hemisphere occurs from the Mackenzie Valley westward through Alaska.

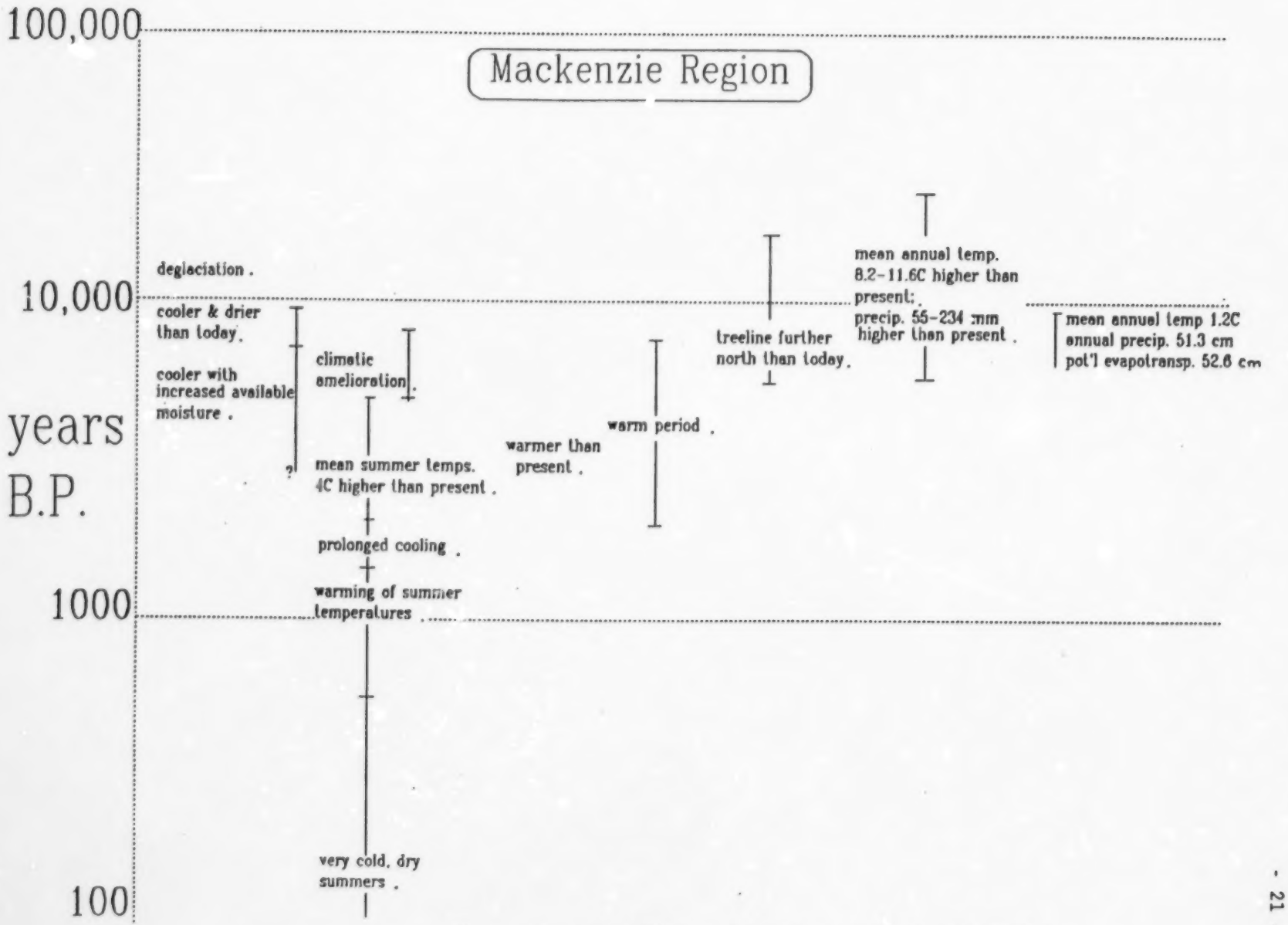

Figure 8. Past climate change in the Mackenzie region using proxy data. Data plotted is taken from AES (1985).

present (B.P.) the mean annual temperatures were about 11°C warmer than at present. During that time Greenland ice core analyses indicate temperatures slightly cooler than today (Saltzman, 1987). This implies that the climate system was operating quite differently than today. It certainly suggests that the Mackenzie region is capable of experiencing much warmer temperatures than it currently experiences, even within a global climate which was probably cooler!

Figure 9 (AES, 1985), which shows climate reconstructed from paleo data, illustrates the climate of the Mackenzie region in historical times up to 1970. More recently though, since the 1970's, northwestern Canada and Alaska have shown a particularly strong warming trend the effect of which has been observed in permafrost temperature profiles (Lachenbruch and Marshall, 1986).

With respect to changes in climate in the Mackenzie Valley region, all GCM models predict a large January warming of up to 11°C, although there is up to a 4°C difference in the magnitudes. July warmings are much smaller, ranging from zero to around 5°C depending upon the model. All models show an increase in annual precipitation ranging from about 10% to 40%, (Etkin, 1990). North of the mainland, winter and summer sea ice is reduced significantly. When the GCM models are run in a $1xCO_2$ control mode, they do not show the mesoscale features evident on climate analyses using real data. These errors, although large enough to give one pause, do not necessarily invalidate the model results; a scenario of regional warming can be created by superimposing model warming on real temperatures, instead of model temperatures. This is based upon the assumption that the difference between 1x and $2xCO_2$ model outputs is reasonable, even though the $1xCO_2$ specification of a base climate may be in error by a magnitude similar to the modelled change.

9 Regional climate impact studies

In spite of the uncertainties associated with developing regional climate predictions, many impact studies require this level of detail. Some of the problems relating to regional impact studies have been reviewed by Cohen (1990). As a result, various climate scenarios have been used as a basis for such studies. Climate scenarios can potentially be based upon paleoclimate data (which are based upon a physically realistic climate but tend to be coarse and probably represent a world with different boundary conditions); instrumental data such as by Brown and Walsh (1986) (which are based upon a physically realistic climate and provide a high level of detail but generally do not provide a large range of scenarios without significant extrapolation); and upon numerical climate models

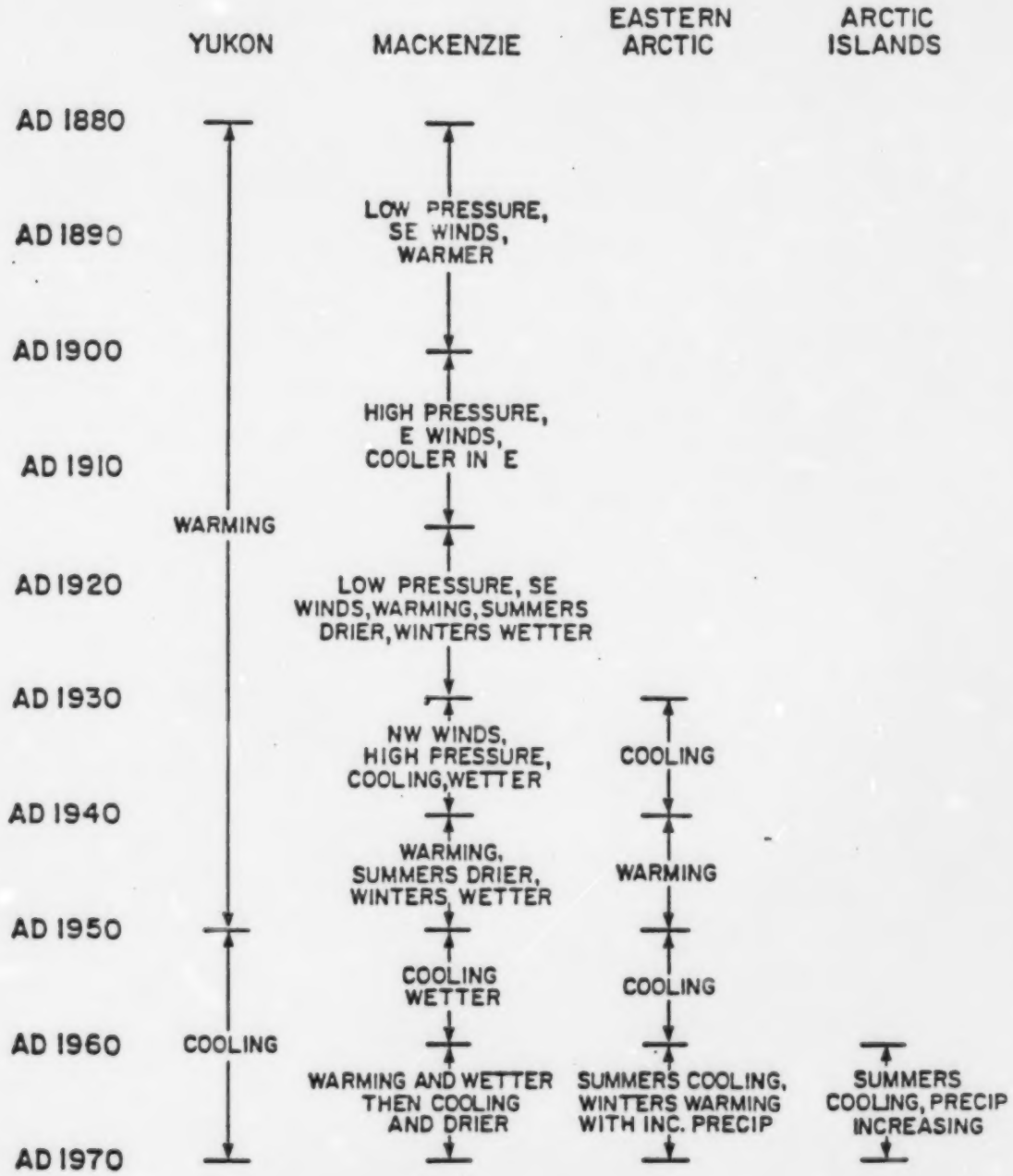

Figure 9. Canadian Arctic climate trends in historic times (AES, 1985).

(which are based upon model rather than real climates, but provide an opportunity to manipulate boundary conditions and to do sensitivity studies in a way not possible using real paleo or instrumental data). For an interesting discussion of the nature of computer climate models the reader is referred to Shuttleworth (1990), and the world of modellion.

There are numerous regional impact studies and proposed studies based upon a variety of climate change scenarios. An overview of likely impacts in the Arctic are summarized in Chapin (1991), Parry et al. (1987) and AES (1986). Some examples of studies relevant to northern latitudes are:

1. A Spatial Permafrost Model for Northern Canada and Its Application to Scenarios of Climate Change (Stuart, 1986)
2. Climate Change and Transportation in Northern Canada: An Integrated Impact Assessment (Lonergan and Woo, 1990).
3. An Overview of Potential Effects of Rapid Warming on the Canadian Arctic (Lonergan, 1989).
4. An east coast ice severity study (Marko et al., 1990)
5. Potential impacts of climate change on Beaufort Sea offshore oil and gas development (in progress under contract to AES).

Cohen and Maxwell (1990) proposed a multi-year integrated impact study of the Mackenzie Valley involving federal/provincial/territorial governments, universities, private industry, native groups etc. This study will address such areas as hydrology, permafrost, vegetation and wildlife, sea ice, sea-level rise and socio-economic sectors.

Among the new tools being developed for regional impact studies are regional climate models, also called Limited Area Models (LAMs). Like the GCMs, LAMs are physically based, but have a much finer resolution than GCMs, within which they are nested. These types of models have been used for many years for weather forecasting, but their application to climate studies is recent. Since they are nested, although they would give much more detail than a GCM output, they will not reduce the differences between the various GCM models (their boundary conditions are driven by the GCMs in a non-interactive mode). They can, however, potentially provide more detailed sensitivity studies of local climate response to a larger scale climate change. One particularly useful application would be an evaluation of the annual sea ice cycle in a warmer Arctic. An operational LAM is described in Dickinson et al. (1989), who found that a resolution of 60 km (as opposed to about 500 km in GCMs) adequately resolved mesoscale circulation in the western United States. Another such model development project has been proposed by the National Center for Atmospheric Research (NCAR Proposal no. 89-36), ie. 'Regional Climate Modeling of the Great Lakes Basin and Climate Change Scenario Development for Impacts Assessment' (Giorgi et al., 1989). The National Oceanic and Atmospheric Administration of the U.S.A. (NOAA) is considering developing a regional atmospheric model for the Arctic (IARPC,

1990; ARCSS, 1990). It should be noted that LAM development with respect to climate change modelling is still in its infancy.

10 Conclusions and recommendations

Well, what can one conclude?

(1) Useful information is available, more so on larger spatial scales than on smaller. Confidence relating to regional predictions below the continental scale is very low.

(2) Uncertainty with respect to the degree and rate of climate change cuts both ways; as pointed out by various critics climate may change much slower than predicted by climate models, but could also change more rapidly.

(3) Uncertainty will probably remain an issue with respect to greenhouse warming for the foreseeable future, and as a result the detailed climate prediction on a regional scale needed for some kinds of impact studies may not be attainable.

(4) If current climate predictions regarding the rate and magnitude of warming over the next century are even approximately correct, then global warming will probably occur on an unprecedented scale.

(5) Annual warming in arctic latitudes will be several times larger than further south (mostly as a result of winter warming). Temperature variability will probably decrease, although the frequency of extreme events may change very significantly as compared to 'normal' climate. Precipitation will generally increase, become more convective and more variable. The strength of the arctic inversion will decrease. Impacts on climate sensitive sectors such as snow and ice will be massive.

For a region such as the Mackenzie Valley, the understanding of historical and current climate is essential in terms of developing reasonable scenarios of future climate change. Examples of processes which need to be assessed for this particular region are:

a) the mechanism controlling the recent strong warming needs to be better understood, especially in terms of how that mechanism might relate to greenhouse warming,
b) the effect of a weakened arctic inversion in terms of local topoclimate and its importance with respect to mesoscale climate,
c) the impact of reduced sea ice on incursions of arctic airmasses into the valley,

d) the sensitivity of the Mackenzie Valley region to shifts in climate and extreme climatic events (such as ENSO), through a study of historical and paleoclimate data.

11 References

AES, 1985. Past Climatic Change in the Canadian Arctic. CCC report 85-14. 101 pp. plus appendix

Arctic System Science (ARCSS), 1990. Proceedings, Workshop on Arctic System Science: A Plan for Action. 26 Feb. - 2 March, 1990, Boulder, Colorado. In Press.

Barnola, J.M., Raymaud, D., Korotkevick, Y.S. and Lorius, C., 1987. Vostol Ice Core Provides 160,000 year Record of Atmospheric CO_2 , Nfature, vol. 329, pp. 408-414.

Blanchet, J.P., 1989. Toward Estimation of Climatic Effects Due to Arctic Aerosols. Atmospheric Environment, vol. 23, no. 11, pp. 2609-2625.

Bolin, B., Jager, J. and Doos, B.R. (eds.), 1986. The Greenhouse Effect, Climatic Change, and Ecosystems. A Synthesis of Present Knowledge. SCOPE 29, J. Wiley and Sons, Chichester, 579 pp.

Brown, R. and Walsh, K., 1986. Canadian Seasonal Climate Scenarios for a CO2 -Induced Global Warming. Canadian Climate Centre Report no. 86-14. 132 pp.

Budyko, M.I. and Izrael, Y., 1987. Anthropogenic Climate Change. Gidrometeorizdat, 406 pp.

Burns, B.M., 1974. The Climate of the Mackenzie Valley - Beaufort Sea. Atmospheric Environment Service Climatological Studies no. 24. vol. 1, 223 pp.

Chapin, T. (editor), 1991. Arctic Ecosystems in a Changing Climate: An Ecophysiological Perspective. Academic Press, in press.

Cohen, S.J., 1990. Bringing the Global Warming Issue Closer to Home: The Challenge of Regional Impact Studies. Bulletin of the American Meteorological Society, vol. 71, no. 4, pp. 520-526.

Cohen, S.J. and Maxwell, J.B., 1990. Impacts of Projected Global Warming: A Research Proposal Mackenzie Basin. International Conference on the Role of the Polar Regions in Global Change. June 11-15, University of Alaska Fairbanks. pp. 53.

Crowley, T.J., 1990. Search for Geological Analogs for the Greenhouse Warming. In: Symposium on Global Change Systems, A.M.S., Anaheim California, Feb. 5-9. pp. 104.

Cubasch, U. and Cess, R., 1990. Processes and Modelling. In: Climate Change, The IPCC Scientific Assessment, Working Group 1, Cambridge University Press, 365 pp.

Delorme, L.D. and Zoltai, S.C., 1984. Distribution of an Arctic Ostracod Fauna in Space and Time. Quaternary Research, vol. 21.

Dickinson, R.E., Errico, R.M., Giorgi, F. and Bates, G.T., 1989. A Regional Model for the Western United States. Climatic Change, vol. 15, pp. 383-422.

Etkin, D.A., 1989. Elevation as a Climate Control in Yukon. Inversion, no. 2, pp. 12-14.

Etkin, D.A., 1990. Greenhouse Warming: Consequences for Arctic Climate. Journal of Cold Regions Engineering, vol. 4, no. 1, pp. 54-66.

Etkins, R., 1989. Global Climate Variations Over the Past Century and the Greenhouse Effect: A Report Based on the First Climate Trends Workshop. CO_2 Induced Climate Change Workshop, DOE, Amherst, Mass., May 8-12, 26 pp.

Folland, C.K., Karl, T.R. and Vinnikov, K.Ya., 1990. Observed Climate Variations and Change. In: Climate Change, The IPCC Scientific Assessment, Working Group 1, Cambridge University Press, 365 pp.

French, H. (ed.), 1986. Proceedings, Impact of Climatic Change on the Canadian Arctic. March 3-5. Orillia, Ontario, 171 pp.

Genthon, C., Barnola, J.M., Raynaud, D., Lorius, C., Jouzel, J., Barkov, N.I., Korotkevich, Y.S. and Kotlyakov, V.M., 1987. Voskok Ice Core: Cllimatic REsponse to CO_2 and Orbital Forcing Changes Over the Last Climatic Cycle. Nature, vol. 329, pp. 414-418.

Giorgi, F., Mearns, L.O. and Schneider, S.H., 1989. Regional Climate Modeling of the Great Lakes Basin and Climate Change Scenario Development for Impacts Assessment. A Proposal to the U.S. EPA, NCAR proposal no. 89-36.

Grotch, S.L., 1988. Regional Intercomparisons of General Circulation Model Predictions and Historical Climate Data. U.S. DOE report TR041. 288 pp.

Gutowski, W.J., Gutzler, D.S., Portman, D., and Wang, W.C., 1988. Surface Energy Balance of Three General Circulation Models: Current Climate and Response to Increasing Atmospheric CO_2. U.S. DOE report TR042. 119 pp.

Hansen, J., Rind. D., DelGenio, A., Lacis, A., Lebedeff, S., Prather, M., Ruedy R., and Karl, T., 1989. Regional Greenhouse Climate Effects. In: Proceedings, Second North American Conference on Preparing for Climate Change, Dec. 6-8, 1988, Washington D.C., pp. 68-81.

Harte, J. and Williams, J., 1988. Arctic Aerosol and Arctic Climate: Results from an Energy Budget Model. Climatic Change vol. 13, pp. 161-189.

Harvey, L.D.D., 1988. On the Role of High Latitude Ice, Snow, and Vegetation Feedbacks in the Climatic Response to External Forcing Changes. Climatic Change, vol. 13, pp. 191-224.

Hengeveld, H., 1990. Controversy About Global Warming. In: CO_2 Climate Report no. 90-01, Environment Canada,.

Idso, S.B., 1987. The CO_2/Trace Gas Greenhouse Effect: Theory Versus. Reality. Theoretical and Applied Climatology, vol. 38, pp. 55-56.

Idso, S.B., 1988. Greenhouse Warming or Little Ice Age Demise: A Critical Problem for Climatology. Theoretical and Applied Climatology, vol. 39, pp. 54-56.

Interagency Arctic Research Policy Committee (IARPC), 1990. Brown, J., Fiske, S., Haugh, J., Hohnson, L., Hohnson, P. and Bowen, S. editors. Arctic Research of the United States, vol. 4, spring 1990, 120 pp.

Jones, P.D., Wigley, T.M.L. and Wright, P.B., 1986. Global Temperature Variations Between 1861 and 1984. Nature, vol. 322, pp. 430-434.

Jones, P.D., Wigley, T.M.L., Folland C.K. and Parker, D.E., 1988. Spatial Patterns in Recent Worldwide Temperature Trends. Climate Monitor, vol. 16, pp. 175-185.

Lachenbruch, A.H. and Marshall, B.V., 1986. Changing Climate: Geothermal Evidence from Permafrost in the Alaskan Arctic. Science, vol. 234, pp. 689-696.

Lashof, D.A., 1989. The Dynamic Greenhouse: Feedback Processes that May Influence Future Concentrations of Atmospheric Trace Gases and Climatic Change. Climatic Change, vol. 14, pp. 213-242.

Lewis, S., 1988. Policy Keynote Speech. In: Proceedings, Second North American Conference on Preparing for Climate Change, Dec. 6-8, Washington D.C.

Lindzen, R.S., 1990. Some Coolness Concerning Global Warming. Bulletin of the American Meteorological Society, vol. 71, no. 3, pp. 288-299.

Lonergan, S.C., 1989. An Overview of Potential Effects of Rapid Warming on the Canadian Arctic. In: Proceedings, Second North American Conference on Preparing for Climate Change, Dec. 6-8, 1989, Washington D.C.

Lonergan, S.C. and Woo, M.K., 1990. Climate Change and Transportation in Northern Canada: An Integrated Impact Assessment. AES contractors report, Downsview, Canada. 160 pp.

Lorenz, E.N., 1989. Chaos, Spontaneous Climatic Variations, and Detection of the Greenhouse Effect. CO_2 Induced Climate Change Workshop, DOE, Amherst, Mass., May 8-12, 26 pp.

Luther, F.M. and Cess, R.D., 1985. Review of the Recent Carbon Dioxide-Climate Controversy. In: Projecting the Climatic Effects of Increasing Carbon Dioxide. DOE Report 237. M.C. MacCracken and F.M. Luther (editors), pp. 321-336.

MacCracken, M.C., 1985. Carbon Dioxide and Climate Change: Background and Overview. In: Projecting the Climatic Effects of Increasing Carbon Dioxide. DOE Report 237. M.C. MacCracken and F.M. Luther (editors), pp. 1-24.

Manabe, S. and Stouffer, R.J., 1988. Two Stable Equilibria of a Coupled Ocean-Atmosphere Mode. Journal of Climate, vol. 1, pp. 841-866.

Manabe, S., Bryan, K. and Spelman, M.J., 1990. Transient Response of a Global Ocean - Atmosphere Model to a Doubling of Atmospheric Carbon Dioxide. Journal of Physical Oceanography, In press.

Marko, J.R., Fissel, D.B., Wadhams, P. and Kelly, P.M., 1990. An Evaluation of the Feasibility of Assessing Effects of Global Warming on Ice Severities off Canada's East Coast. Contractors report for AES Ice Branch. Draft Report, 40 pp.

Marshall Institute, 1989. Scientific Perspectives on the Greenhouse Problem. George C. Marshall Institute, Washington D.C. 37 pp.

Maxwell, J.B. and Barrie, L.A., 1989. Atmospheric and Climatic Change in the Arctic and Antarctic. Ambio, vol 18., no. 1. pp. 42-49.

Meehl, G.A. and Washington, W.M., 1990. CO_2 Climate Sensitivity and Snow-Sea-Ice Albedo Parameterization in an Atmospheric GCM Coupled to a Mixed-Layer Ocean Model. Climatic Change, vol. 16, pp. 283-306

Mitchell, J.F.B., 1989. The Equilibrium Response to Doubling Atmospheric CO_2. CO_2 Induced Climate Change Workshop, DOE, Amherst, Mass., May 8-12, 26 pp.

Mitchell, J.F.B., Manabe, S., Meleshko, V. and Tokioka, T., 1990. Equilibrium Climate Change - and its implications for the future. In: Climate Change, The IPCC Scientific Assessment, Working Group 1, Cambridge University Press, 365 pp.

Parry, M.L., Carter, T.R. and Konijn, N.T. (eds.), 1987. The Impact of Climatic Variations on Agriculture. Volume 1: In Cool Temperature and Cold Regions.

Ramanathan, V., Callis, L., Cess, R., Janses, J., Isaksen I., Kihn, W., Lacis, A., Luther, F., Mahlaman, J., Reck, R., and Schlesinger, M., 1987. Climate-Chemical Interactions and Effects of Changing Atmospheric Trace Gases. Reviews of Geophysics, vol. 25, no. 7, pp. 1441-1482.

Reifsnyder, W.E., 1989. A Tale of Ten Fallacies: The Skeptical Enquirer's View of the Carbon Dioxide/Climate Controversy. Agricultural and Forest Meteorology, vol. 47, pp. 349-371.

Rind, D., Goldber, R. and Ruedy, R., 1989. Change in Climate Variability in the 21st Century. Climatic Change, vol. 14, pp. 5-37.

Roots, E.F., 1989. Climate Change: High-Latitude Regions. Climatic Change vol. 15, pp. 223-253

Saltzman, B. (editor), 1983. Theory of Climate. Advances in Geophysics, vol. 25, 505 pp.

Schlesinger, M.E., 1984. Climate Model Simulations of CO_2-Induced Climatic Change. Advances in Geophysics, vol. 26, pp. 141-235.

Schlesinger, M.E., 1986a. Equilibrium and Transient Climatic Warming Induced by Increased Atmospheric CO_2 . Climate Dynamics, vol. 1, pp. 35-51

Schlesinger, M.E., 1986b. General Circulation Model Simulations of CO_2 -Induced Equilibrium Climate Change. In: Proceedings, Impact of Climatic Change on the Canadian Arctic, March 3-5, Orillia, Ontario, H. French (editor), pp. 15-52.

Schlesinger, M.E. and Mitchell, J.F.B., 1985. Model Projections of the Equilibrium Climatic Response to Increased Carbon Dioxide. In: Projecting the Climatic Effects of Increasing Carbon Dioxide. DOE report 237. M.C. MacCracken and F.M. Luther (editors). pp. 81-148.

Schneider, S.H., 1988. The Greenhouse Effect: Reality or Media Event. In: Proceedings, Second North American Conference on Preparing for Climate Change, Dec. 6-8, Washington D.C. pp. 57-67.

Shuttleworth, W.J., 1990. The Modellion Concept - Observational Studies of Land/Atmosphere Interaction. In: Symposium on Global Change Systems, Special Sessions on Climate Variations and Hydrology, A.M.S., Anaheim California, Feb. 5-9. pp. 46-53.

Smith and Tirpak (eds.) (1989). The Potential Effects of Global Climate Change on the United States. Report to Congress by the Environmental Protection Agency, 413 pp.

Stouffer, R.J., Manabe, S. and Bryan, K., 1990. Climatic Response to a Gradual Increase of Atmospheric Carbon Dioxide. In: Symposium on Global Change Systems, Special Sessions on Climate Variations and Hydrology, A.M.S., Anaheim California, Feb. 5-9. pp. 11-17.

Stuart, A., 1986. A Spatial Permafrost Model for Northern Canada and Its Application to Scenarios of Climate Change. Canadian Climate Centre Report no. 86-15. Atmospheric Environment Service, Downsview, Canada.

Stuart, A., Etkin, D.A. and Judge, A.S., 1990. Recent Observations of Air Temperature and Snow Depth in the Mackenzie Valley Area and their Implications on the Stability of Permafrost Layers. Atmospheric Environment Service, CCC report in press.

Sutherland, D.G., 1990. Ice Masses on the Move. Nature, vol. 346.

Tsonis, A.A. and Elsner, J.B., 1989. Testing the Global Warming Hypotheses. Geophysical Research Letters, vol. 16, no. 8, pp. 795-797.

Vinnikov, K.Ya., Groisman, P.Ya. and Lugina, K.M., 1990. Empirical Data on Contemporary Global Climate Changes (Temperature and Precipitation). Journal of Climate, vol. 3, pp. 662-677.

Washington, W.M. and Meehl, G.A., 1989. Climate Sensitivity Due to Increases CO_2: Experiments With a Coupled Atmosphere and Ocean General Circulation Model. Climate Dynamics, vol. 4, pp. 1-38.

Watts, R.G. and Morantine, M., 1990. Rapid Climatic Change and the Deep Ocean. Climatic Change, vol. 16, pp. 83-97.

Wigley, T.M.L., 1988. The Effect of Changing Climate on the Frequency of Absolute Extreme Events. Climate Monitor, vol. 17, no. 2, pp. 44-54.

Wigley, T.M.L., Angell, J.K. and Jones, P.D., 1985. Analysis of the Temperature Record. In: Detecting the Climatic Effects of Increasing Carbon Dioxide. DOE Report 235, M.C. MacCracken and F.M. Luther (editors), pp. 55-90.